PHYSICAL REVIEW D **84**, 095015 (2011)

Revisiting light neutralino scenarios in the MSSM

Daniel Albornoz Vásquez,[1] Geneviève Bélanger,[1] and Céline Bœhm[1,2]
[1] *LAPTH, U. de Savoie, CNRS, BP 110, 74941 Annecy-Le-Vieux, France*
[2] *IPPP, Ogden centre, Durham University, UK*
(Received 11 August 2011; revised manuscript received 26 September 2011; published 11 November 2011)

We revisit the case of a light neutralino lightest supersymmetric particle in the framework of the minimal supersymmetric standard model. We consider a model with 11 free parameters. We show that all scenarios where the annihilation of light neutralinos rely mainly on the exchange of a light pseudoscalar are excluded by direct detection searches and by Fermi measurements of the γ-flux from dwarf spheroidal galaxies. On the other hand, we find scenarios with light sleptons that satisfy all collider and astroparticle physics constraints. In this case, the lower limit on the lightest supersymmetric particle mass is 12.6 GeV. We discuss briefly how the parameter space of the model could be further probed at the LHC.

DOI: 10.1103/PhysRevD.84.095015 PACS numbers: 14.80.Ly, 12.60.Jv

I. INTRODUCTION

Motivated by the possible annual modulation signals reported by DAMA [1] and CoGeNT [2] that are compatible with a light dark matter candidate (DM), several groups have recently reinvestigated supersymmetric scenarios with a lightest supersymmetric particle (LSP) around 10–30 GeV. Within the context of the minimal supersymmetric standard model (MSSM), such a light neutralino LSP can only be obtained by relaxing the unification condition on the gaugino masses such that $M_1 \ll M_2$ [3–11]. When this condition is satisfied, most of the stringent LEP constraints (in particular the limit of 46 GeV [12] on the lightest neutralino obtained within the framework of the constrained-MSSM) are removed. Only the LEP constraints from the invisible width of the Z boson and the production of the LSP with one of the heavier neutralinos remain in the neutralino sector. Light neutralinos are then constrained mainly by the relic density measurement as well as by the Higgs and the flavor sector, in particular, from B-physics.

For very light neutralinos, with a mass below 10 GeV, the Wilkinson microwave anisotropy probe (WMAP) upper bound can be satisfied when M_A, the pseudoscalar mass, is around 100–150 GeV and $\tan\beta$ is large [13–17]. This corresponds to a set of parameters that leads to large deviations in the flavor sector [10]. Furthermore, this range of parameters faces severe constraints from collider searches for the heavy Higgs doublet produced in association with b quarks and decaying into tau pairs at the Tevatron and the LHC [18–20]. Indeed, at large values of $\tan\beta$ and for a light pseudoscalar, the cross section for this process is strongly enhanced. The light neutralino scenarios that survive all collider and cosmological constraints are then challenged by the upper limits from direct detection searches [11]. Light neutralinos can also lead to strong signals in indirect searches both for the photon flux [21] or for the antiproton flux [22–24].

For heavier neutralinos, the WMAP condition can also be satisfied when a pair of LSP's annihilate into fermions through sfermion exchange or through Z exchange. The former requires light sleptons –these are, however, subject to LEP constraints– while the latter is efficient when the mass of the LSP pair approaches the Z mass. In either case, a light pseudoscalar is no longer needed and such scenarios can escape all constraints [3,8,11,15,25].

In Ref. [11], an exploration of the MSSM with eight free parameters based on an Markov chain Monte Carlo (MCMC) approach, showed that neutralino candidates below 15 GeV were severely constrained by Higgs searches as well as by direct detection searches, in particular, by XENON100 [26]. Such a conclusion was challenged in [4,6] as well as very recently in [8].

In view of these results, we revisit in this paper the case of light neutralinos in the MSSM. We have extended our previous study in several ways. First, we increase the number of free parameters of the model to 11, adding the gluino mass, decorrelating the third generation squark masses from the other two and splitting the left- and right-handed slepton masses. The first two parameters affect mainly the flavor sector and do not impact directly on the very light neutralino candidates. Splitting the slepton mass and exploring carefully the region where sleptons are just above the LEP limit allows to find new scenarios where neutralinos annihilate via light slepton exchanges. Second, we have also updated the limits on the Higgs sector, in particular, exploring more carefully the region where all Higgses are around 100 GeV. This allows to find new scenarios with $m_{\chi_1^0} \lesssim 15$ GeV satisfying the Tevatron limits on the search for the heavy Higgs doublet. However, we show that recent CMS results [19,20] for Higgs searches at the LHC further constrain a large fraction of the light neutralino scenarios and that all these scenarios are excluded by the XENON100 experiment. We have also computed the fluxes of gamma rays from dwarf spheroidal galaxies (dSph) and used the limits from Fermi-LAT to constrain all scenarios with a light pseudoscalar. We find a lower bound on the neutralino mass at 12.6 GeV after including the updated constraints from both colliders and astroparticle physics. These light neutralinos are always associated with sleptons just above the LEP limit. We also briefly discuss how these results will be affected by upcoming LHC results on sparticle searches and on B-physics observables.

This paper is organized as follows: in Sec. II, we summarize the various constraints on the model; in Sec. III, we find the lower bound on the neutralino mass and emphasize the impact of astrophysical constraints. In Sec. IV, we discuss implications for LHC observables. A discussion and comparison with other studies is presented in Sec. V.

II. CONSTRAINTS ON LIGHT NEUTRALINOS

We consider the MSSM with 11 free parameters defined at the electroweak scale, as listed in Table I, and we assume $A_b = A_\tau = 0$. These parameters only play a role in the mixing in the down sector ($\propto A_{b(\tau)} - \mu \tan\beta$), while a large mixing can be induced by $\mu \tan\beta$. To explore the parameter space, we have used the Markov chain Monte Carlo code presented in [11], which is based on MICROMEGAS [27–29] for the computation of collider and flavor constraints as well as for dark matter observables. We rely on SUSPECT [30] for the computation of the spectrum. The constraints imposed are listed in Table I of Ref. [11]. They include the WMAP constraint on the abundance of dark matter [31], branching ratios for $B(b \to s\gamma)$, $B(B_s \to \mu^+\mu^-)$, $R(B \to \tau\nu)$, the muon anomalous magnetic moment, $(g-2)_\mu$ as well as LEP limits on sparticle masses, on the invisible width of the Z and on the associated production of the LSP with a heavier neutralino. For the LEP limits, we have used the values implemented in MICROMEGAS, corresponding, in particular, to the values for the sleptons, $m_{\tilde{e}} > 100$ GeV, $m_{\tilde{\mu}} > 99$ GeV, $m_{\tilde{l}_1} > 80.5$ GeV, and $m_{\tilde{\nu}} > 43$ GeV.[1]

In this analysis, we have replaced the limit on the light Higgs mass with improved limits on the Higgs sector obtained from the HIGGSBOUNDS3.1.3 package [32,33] linked to MICROMEGAS2.4. In this way, we take into account both the LEP constraints on the light Higgs as well as Tevatron constraints on heavy Higgs searches at large $\tan\beta$. The likelihood for the Higgs constraint is taken to be 0 when a point is rejected by HIGGSBOUNDS and 1 otherwise. We compute the global weight $\mathcal{Q}$ by multiplying the global likelihood to the global prior of each scenario. We use the likelihood and prior functions described in [11].

We have not included recent LHC results on heavy Higgs searches [19,20] in the fit but impose them *a posteriori*. Also, we have not included the recent results from the LHC on squarks and gluino searches as they are somewhat model dependent. Note that when imposing cosmological constraints we allow for the possibility that neutralinos do not explain all of the dark matter in the universe but only a fraction taken to be as small as 10%; this has no major impact on our conclusions since light neutralinos tend to be over abundant.

[1]We have not included the flavor constraint from $K \to l\nu$, although constraining the light charged Higgs as shown in [6], this has no direct influence on the light neutralino.

TABLE I. Intervals for MSSM-free parameters (GeV units).

Parameter	Minimum	Maximum	Tolerance
M_1	1	1000	3
M_2	100	2000	30
M_3	500	6500	10
μ	0.5	1000	0.1
$\tan\beta$	1	75	0.01
M_A	1	2000	4
A_t	−3000	3000	100
$M_{\tilde{l}R}$	70	2000	15
$M_{\tilde{l}L}$	70	2000	15
$M_{\tilde{q}1,2}$	300	2000	14
$M_{\tilde{q}3}$	300	2000	14

Light neutralinos can also be constrained by direct and indirect detection. We will apply these constraints only after having selected the best scenarios from a global fit. Specifically, we will consider the XENON100 results from direct detection searches. In all cases with two scalar Higgses with a mass around 100 GeV that must couple sufficiently to the LSP to provide enough annihilation in the early universe, we expect an important contribution of both Higgses to the spin independent neutralino nucleon elastic scattering cross section. This will turn out to be an important constraint on light neutralinos as will be discussed in the next section.

Pair annihilation of neutralino DM into quarks and/or τ's leads, after hadronization, to the production of gamma rays. Photons can also be radiated directly from an internal line or from a final state before it decays. The photon flux is proportional to $1/m^2_{\chi^0_1}$, thus a large flux is expected for light dark matter. The observation of the photon flux from dwarf spheroidal galaxies (dSph) by Fermi-LAT therefore provides a constraint on light neutralino dark matter. For each viable scenario found by the MCMC, we have computed the gamma ray flux expected in the eight dwarfs observed by the Fermi experiment. This value is then compared with the Fermi-LAT 95% limits [34] with the procedure described in [21]. The most stringent limits are obtained for the Draco dSph.

III. THE LOWER LIMIT ON THE NEUTRALINO MASS

Viable scenarios with light neutralinos can be difficult to find. Therefore, we have imposed the prior $m_{\chi^0_1} < 30$ GeV. Since we already know that there are neutralinos at around $\sim$28 GeV [11], there is no need to probe higher masses, which would make the run less efficient.

Performing the MCMC analysis, we found the maximum weight to be $\mathcal{Q}_{\rm max} \simeq 0.72$. Nevertheless, only 2.9% of the points have weights $\mathcal{Q} \geq 0.23$ (1σ away from $\mathcal{Q}_{\rm max}$), while 57% have weights $\mathcal{Q} \geq 2.2 \times 10^{-3}$ (3σ away from $\mathcal{Q}_{\rm max}$). We find neutralinos with masses as low as 10.5 GeV, although most points are located near 30 GeV, the prior upper bound on the neutralino mass. The allowed parameter space, represented in Fig. 1, is best described in terms of the properties of the neutralinos that satisfy the relic density upper limit. There are three dominant mechanisms that provide efficient neutralino annihilation: A) annihilation into lepton pairs through slepton exchange, B) annihilation via exchange of a light pseudoscalar Higgs, C) annihilation via a Z boson. The latter works better for masses near $M_Z/2$, therefore, neutralinos below $\simeq 25$ GeV are expected to correspond to scenarios A and B.

The first scenarios (A) require a bino LSP and light sleptons, in particular, right-handed sleptons which couple more strongly to the bino. Consequently, we observe a large peak at low values of the soft parameter $m_{\tilde{l}_R}$. Furthermore, large values of $\tan\beta$ will induce a large mixing in the stau sector, thus decreasing the lightest stau mass.[2] As a result, all sleptons are just above the LEP exclusion region. The $\tan\beta$ distribution thus extends to the highest values probed. The other two scenarios (B and C) require a LSP with an as large as possible Higgsino component to ensure sufficient coupling to the Z or the Higgs –this means small μ– even though the LSP is dominantly bino, since $M_1 \ll \mu$. Scenario B further requires a light pseudoscalar, hence the large peak in the distribution at low values of M_A. In this case, large values of $\tan\beta$ also are needed for efficient annihilation. However, the low M_A—large $\tan\beta$ region is strongly constrained by Tevatron searches. Furthermore, the $R(B_u \to \tau\nu_\tau)$ ratio in the case of a light charged Higgs drops to very low values around $\tan\beta = 25$, thus these values are disfavored. Other parameters are constrained from several observables. For example, a squark contribution is needed to cancel the Higgs contribution in the $B(b \to s\gamma)$, hence the peak at low values of third generation squark masses $M_{\tilde{q}_3}$. This is relevant only for scenario B.

The allowed region displayed in the $\tan\beta - M_A$ plane, Fig. 2, shows that when the pseudoscalar is light, large values of $\tan\beta$ are ruled out after taking into account Tevatron constraints on Higgs decaying into tau pairs. Furthermore, the newer exclusion limit from CMS [20] in the same channel (black line in Fig. 2) further cuts into the parameter space, the only remaining points for $M_A < 150$ GeV correspond to $\tan\beta \leq 14$.

[2]For large enough mixing in the $\tilde{\tau}$ sector, the Higgsino component of the LSP also contributes to annihilation into τ pairs, hence the preference for small values of μ.

To ensure that we have probed completely light neutralino scenarios, we did a further run imposing a prior $m_{\chi_1^0} < 15$ GeV. The maximum weight in that region is of 0.22, and the maximum weight for the points with $M_A < 150$ GeV is $\mathcal{Q} = 0.085$ which is much lower than in the previous sample. The allowed points in the $M_A - \tan\beta$ are displayed in Fig. 3. Here we show only the region with a light pseudoscalar; other points with very large values of $\tan\beta$ and light sleptons were also found and will be discussed below. With the incorporation of the latest Tevatron bounds, we have not found the same configurations as in our previous analysis [11]. Those with large values of $\tan\beta$ are now ruled out by Higgs searches. We found more scenarios where all Higgs bosons are around 100 GeV; indeed, all Higgs bosons have to be light in order to overcome the limits on the Higgs mass from LEP. However, most of these points are now constrained by the latest CMS exclusion [20] imposed after performing the fit. In this sample, there were neutralinos below 10 GeV that passed all collider constraints, albeit with a low weight. However, we will show that all these neutralinos are ruled out by astroparticle limits (both from XENON100 and Fermi-LAT).

The LHC limits in the $m_A - \tan\beta$ plane could be somewhat relaxed when theoretical uncertainties on the Higgs production cross section are taken into account [35], thus allowing more points with light neutralinos. However, as will be shown in the next section, the light neutralinos with large spin independent cross sections are also excluded by two sets of astrophysical constraints. Furthermore, the LHC limits are improving rapidly with the increased accumulated luminosity and the updated exclusion limits reach beyond the ones used in this article [36].

Constraints from astroparticle physics

We now consider two different astroparticle constraints on the light neutralino scenarios. First, we consider the spin independent direct detection limits from XENON100 as it provides the most stringent limit on light neutralinos. Figure 4 represents the yields in the $\xi\sigma^{\rm SI}$ vs. $m_{\chi_1^0}$ plane along with limits from XENON100 and CDMS-II. The three types of scenarios have very different predictions for the spin independent cross section on nucleons. In scenario A, the LSP can be pure bino and therefore couples weakly to the Higgs; cross sections can therefore be much suppressed. It is in this class of scenarios (green points) that we find the lightest viable neutralino. In case B, cross sections which receive a contribution from both light scalar Higgses are large. All these points are ruled out by XENON100 as was found in the previous analysis. In scenario C, the LSP also has a Higgsino component but tends to have a lower cross section on nucleons since it receives only the contribution of one light Higgs. Since a smaller Higgsino component is needed as one approaches the Z resonance, some of these scenarios with mass near

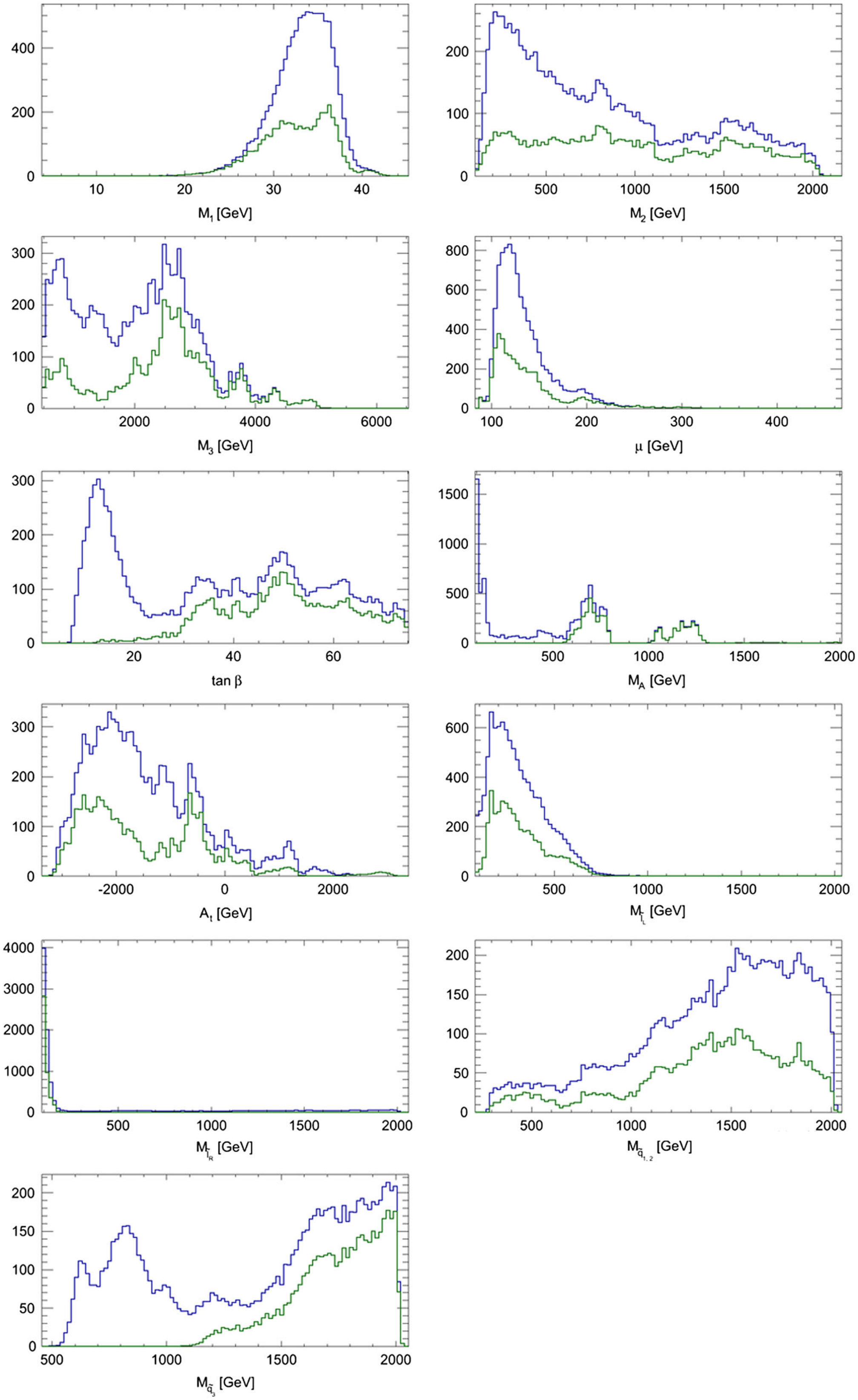

FIG. 1 (color online). Frequency distributions of free parameters in the light MSSM neutralino scenarios. Dark (blue) curves contain all allowed points while light (green) curves show the distribution for the points that pass all astroparticle physics constraints.

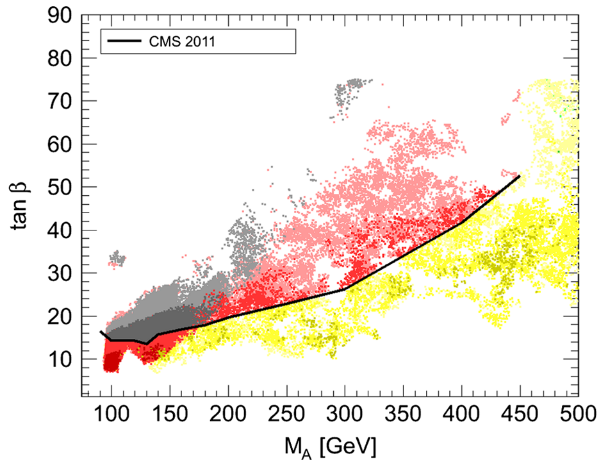

FIG. 2 (color online). Allowed points in the $\tan\beta$ vs. M_A plane in the $m_{\chi_1^0} < 30$ GeV search. We show only the region where $M_A < 500$ GeV. The exclusion limit from CMS is also displayed. Light (yellow) points are excluded by one constraint, while dark (red and gray) points are excluded by 2 or 3 (2 and 3) constraints (CMS, XENON100, and dSph as described in this section). (The shading represents $\mathcal{Q}$: weights of darker points are at most at 1σ from $\mathcal{Q}_{\max}$ while the lighter points are at most at 2σ and 3σ.)

30 GeV predict an elastic scattering cross section below the limit of XENON100. When computing these predictions, we have chosen rather conservative values for the quark coefficient in the nucleon ($\sigma_{\pi N} = 45$ MeV, $\sigma_0 = 40$ MeV) although recent lattice QCD results [37] indicate that the s-quark content could be smaller than previously thought, leading to a suppression of the SI cross sections. Taking the central value from the lattice result would only lead to a 20% further reduction in the neutralino proton cross section. This is not enough to make some of the scenarios B drop below the XENON100 exclusion limit.

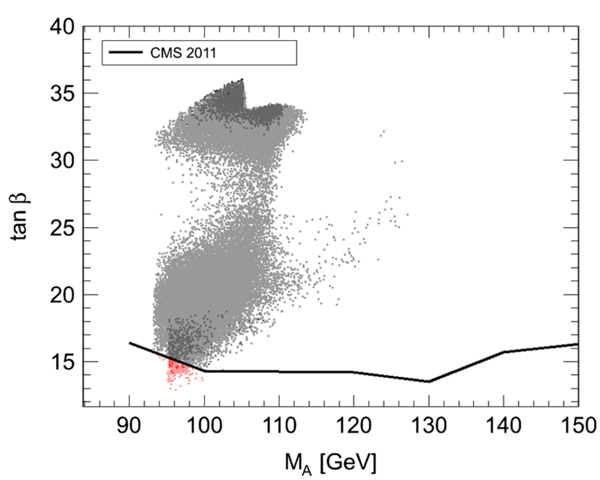

FIG. 3 (color online). Allowed points in the $\tan\beta$ vs. M_A plane with the prior $m_{\chi_1^0} < 15$ GeV showing only the region where $M_A < 150$ GeV. The exclusion limit from CMS is also displayed. The color code is the same as in Fig. 2

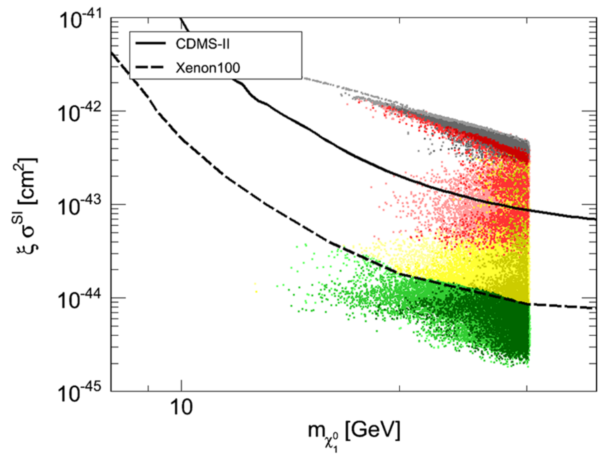

FIG. 4 (color online). Points of the $m_{\chi_1^0} < 30$ GeV search represented in the $\xi\sigma^{\rm SI}$ vs. neutralino mass plane. Exclusion limits from CDMS-II [38] and XENON100 are shown. The color code is the same as in Fig. 2; black (green) points are allowed.

An improvement on the SI direct detection limit by a factor 4–8 is required to close light neutralino scenarios up to 30 GeV.

We now compute the gamma ray flux originating from DM annihilation in dSph assuming a Navarro-Frenk-White [39] profile and compare this with the 95% limits from Fermi-LAT considering an angular region of 0.5° and an integrated flux over 0.1 GeV $< E < m_{\tilde{\chi}_1^0}$. We found that many configurations –more specifically with the characteristics of scenario B– are excluded by both limits (red points) while others are only constrained by XENON100 (yellow points); see Fig. 5. The configurations allowed by XENON100 (green points) satisfy all collider and astrophysical constraints. All these belong to scenario A for

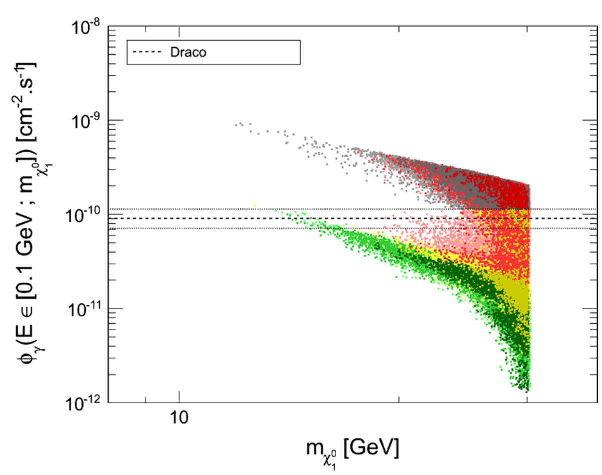

FIG. 5 (color online). Integrated γ-ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 30$ GeV search. We show limits from Fermi-LAT including the 1σ error bars in the integral over the DM density distribution assuming a NFW profile. Same color code as Fig. 4.

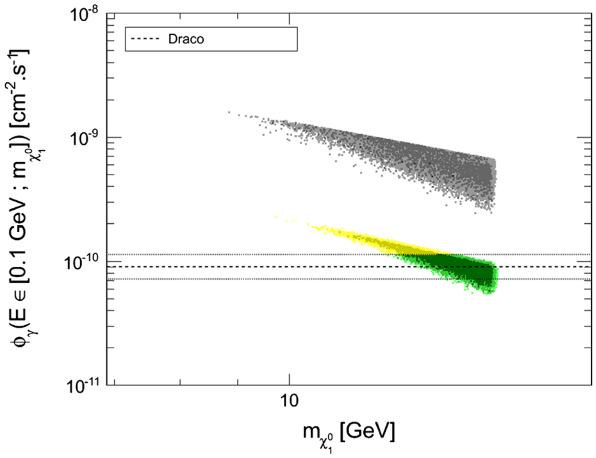

FIG. 6 (color online). Integrated γ-ray flux from the Draco dwarf spheroidal galaxy as a function of the neutralino mass in the $m_{\chi_1^0} < 15$ GeV search. We show limits from Fermi-LAT. Same color code as Fig. 4.

neutralinos below 28 GeV. In these configurations, the photon flux just reached the maximal value allowed by Fermi for the smallest mass (recall that the flux goes as $1/m^2_{\chi_1^0}$).

Since the parameter space allowing for light neutralinos is rather fine-tuned, one might argue that somewhat lighter neutralinos could be found with a refined analysis. With an additional run with a prior set at $m_{\tilde{\chi}} < 15$ GeV, we found that the lower bound on the neutralino could be extended by a few GeV's when considering collider constraints. However, the lighter neutralinos were constrained by dSphs as displayed in Fig. 6. In this run, we found the lower limit on the neutralino mass to be 12.6 GeV, corresponding to a point of weight $\mathcal{Q} \simeq 0.11$ that is safe regarding XENON100, Fermi-LAT, and CMS. As before, it corresponds to scenarios with light sleptons.

After taking into account constraints from direct and indirect DM searches and considering only the points with the highest likelihood, we find that the lightest neutralino has a mass of $m_{\chi_1^0} \simeq 18.6$ GeV, while 12.6 GeV is possible with the prior $m_{\chi_1^0} < 15$ GeV. Other constraints are not a critical issue as the light slepton is favorable for the muon anomalous magnetic moment and the large value for M_A implies that the B-physics constraints are weak. Furthermore, the almost pure bino LSP easily evades the LEP constraints on the Z invisible width. These new configurations were not found in our previous study where we had assumed one common soft slepton mass; furthermore, they rely critically on the exact value taken for the limit on light sleptons. These results are in qualitative agreement with the recent results of [8].

When reaching these conclusions, we have used the exclusion limits from XENON100 and Fermi-LAT. Some uncertainties in the extraction of these limits could relax the constraints on light neutralinos. First, the gamma-ray flux from dSPh's depends on the J-factor that specifies the integral of the squared dark matter density over the line of sight. Uncertainties in the dark matter halo parameter can thus induce large variations in the predicted flux. However, for the Draco dSPh used in this analysis, less than a factor of 2 reduction in the flux is expected [40,41]. This means that the light neutralinos in scenario B are still excluded (the grey points in Fig. 5) while those in scenario A could satisfy the dSPh constraint (the points in yellow in Fig. 6). The lower bound on the neutralino mass would then be of $\mathcal{O}(10)$ GeV. Recall that this bound corresponds to neutralinos with small direct detection cross sections. The limit from XENON100 also suffers from uncertainties arising from the value of the scintillation factor $\mathcal{L}_{\text{eff}}$ and/or from the statistical analysis used. It has been argued that these two factors could reduce the sensitivity of XENON100 at low masses and shift the exclusion by a few GeV's [42], thus reconciling the XENON100 result with the signal of CoGeNT (see, for example, Ref. [17]). However, this is not sufficient to allow new points with light neutralinos and a large SI cross section (scenario A) as those are also excluded by Fermi-LAT as well as by Higgs searches at CMS. These points appear in grey in Fig. 4.

IV. OTHER COLLIDER OBSERVABLES

We now consider the prospects for probing these scenarios at the LHC. For this, we have computed the value for all the observables used for the fit as well as the masses of sparticles. One observable that is promising in the flavor sector is $B(B_s \to \mu^+\mu^-)$, since it is enhanced at large values of $\tan\beta$ and low values of M_A. Even though this region is already constrained from Higgs searches, the predictions for $B(B_s \to \mu^+\mu^-)$ together with the recent

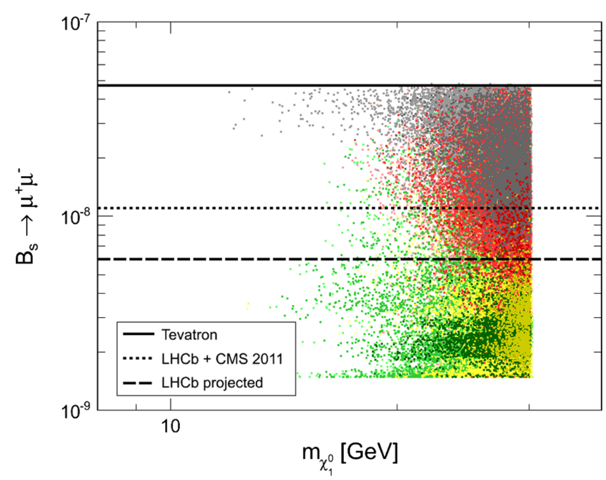

FIG. 7 (color online). Predictions for $Br(B_s \to \mu^+\mu^-)$ as a function of the LSP mass in the $m_{\chi_1^0} < 30$ GeV search. The current Tevatron limit (solid line), the combined LHCb and CMS limit (dotted line) [43] as well as the projected LHCb limit (dashed line) [44] are also displayed. The color code is the same as in Fig. 4.

limit obtained from a combination of LHCb and CMS results [43] as well as expectations for the reach of LHCb [44] show that many scenarios would be either further constrained or lead to a signal in the very near future (see Fig. 7). However, most of the configurations with the best likelihood with neutralinos below 20 GeV predict a rate much below the foreseen limit. These all belong to the scenarios with light sleptons.

As mentioned above, we have not imposed the LHC constraints on squarks and gluinos in the MCMC analysis. We have, however, checked *a posteriori* that these constraints did not impact the lower limit on the neutralino mass. For this we have used the limits set by ATLAS with $\mathcal{L} = 1\ \text{fb}^{-1}$, $m_{\tilde{q}} > 850$ GeV, and $m_{\tilde{g}} > 800$ GeV, in a simplified model where the LSP is massless and the squarks of the first generations are degenerate and assumed to decay uniquely in jets plus missing energy [45]. In our case, the limits are somewhat weaker as the squarks have reduced branching ratios in jets plus missing energy. Even using this more stringent limit, we see that many of the scenarios with a good likelihood have first generation squarks and/or gluinos above the TeV scale, as displayed in Fig. 8. In particular scenarios with the best likelihoods that satisfy all constraints (points in green in Fig. 8) can have $m_{\tilde{g}} \simeq 2$ TeV, near the upper mass range that can be probed with the high energy, high luminosity LHC ($\sqrt{s} = 14$ TeV and $\mathcal{L} = 100\ \text{fb}^{-1}$). This is not surprising since the color sector affects only the light neutralino scenarios through some of the B-physics observables. Of course, many scenarios are constrained by LHC new physics searches; this is particularly significant for scenarios with a light pseudoscalar where a squark/gluino contribution is needed to cancel the Higgs contribution in B-physics observables.

The points that survive all collider and astrophysical limits nevertheless predict some light particles and can

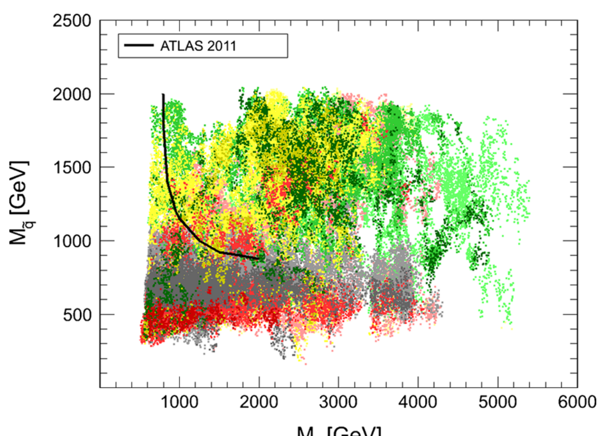

FIG. 8 (color online). Predictions for the lightest squark mass of the first and second generation as a function of the gluino mass. The color code is the same as in Fig. 4. The ATLAS limit on squark and gluino in a simplified model [45] is also displayed for illustration.

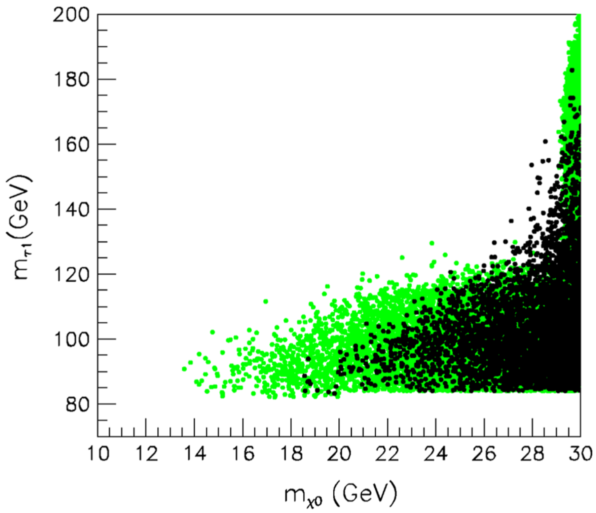

FIG. 9 (color online). Predictions for the lightest slepton mass as a function of the LSP mass for points that pass all collider and astroparticle physics constraints in the $m_{\chi_1^0} < 30$ GeV search. Dark points are those within the 1σ region, and light points within 3σ.

therefore be probed further at the LHC. These points are displayed in the $m_{\tilde{\tau}} - m_{\tilde{\chi}}$ plane in Fig. 9 where it is shown that sleptons with a mass below 120 GeV are predicted in all scenarios where the LSP is below 26 GeV. The slepton pair production cross section at the LHC-7 TeV is around 20–50 fb and leads to a signature with two leptons and missing energy. These scenarios can easily be studied at a future linear collider [46]. Finally, the points with a neutralino near 30 GeV that belong to scenario C (annihilation through a Z exchange) and that also survive all constraints predict the chargino and the second neutralino to be below 200 GeV. Both particles often decay into a LSP and a gauge boson rather than into leptons, hence one cannot exploit the limits from the trilepton searches set by the Tevatron [47,48].

V. DISCUSSION

This analysis shows that there are two windows of configurations with light neutralinos with very different characteristics and signatures. In the first, it is the light pseudoscalar Higgs boson that dominates DM neutralino annihilation. A large fraction of these configurations have been excluded by the recent results from CMS on searches for associated Higgs production decaying into τ pairs. Furthermore, their astroparticle signatures, specifically in the SI direct detection experiments and in the γ-ray signal from dSphs, are largely above the observations published by the XENON100 and the Fermi-LAT collaborations. In the second, light sleptons just above the LEP limit are required to provide efficient neutralino annihilations. The viable configurations feature a heavy pseudoscalar mass ($M_A \gtrsim 500$ GeV), thus the heavy Higgs doublet does not contribute significantly to the SI elastic scattering of neutralinos off nucleons. This, combined with the fact that the LSP is a bino, allows to escape the direct detection constraint. These scenarios are safe regarding indirect detection limits. The absolute lower bound on the light neutralino is found to be 12.6 GeV (or 11.1 GeV when uncertainties on the photon flux from dSph's are taken into account).

The results presented here appear to disagree somewhat with [4,6], which obtain neutralinos lighter than 10 GeV accompanied with light pseudoscalars after taking into account collider limits. This could be explained by the fact that there are some differences as to the constraints taken into account –we used a slightly more stringent constraint on the Higgs sector and on $B(B_s \to \mu^+\mu^-)$ and $R(B \to \tau\nu)$ as compared to [4]– and/or on the definition of the allowed points –combined likelihood in our case and 2σ bound in other works. To verify this, we have also performed a random scan of the parameter space using the procedure described in [6] and found similar results. In any case, we claim that all these scenarios are constrained by dSphs and by direct detection. The absolute lower bound on the light neutralino that we find is in agreement with the one found in Ref. [3] and in [8]. In these analyses, light sleptons are required to ensure sufficient annihilation of the bino LSP.

In conclusion, the light neutralino scenarios that are allowed by collider constraints are in many cases challenged by direct and indirect detection limits. The remaining scenarios do not have a large scattering cross section on nuclei and cannot explain DAMA [1] and CoGeNT [2]. An improvement of less than an order of magnitude on the spin independent direct detection limit would allow to rule out all MSSM neutralinos lighter than 30 GeV while a factor of 2 improvement in sensitivity in gamma-ray searches would probe all neutralinos lighter than 20 GeV. Furthermore, light neutralinos are necessarily accompanied by other new particles at the electroweak scale. In particular, one expects sleptons with a mass $\mathcal{O}(100\text{ GeV})$ when neutralinos are lighter than 26 GeV and/or charginos and other neutralinos with masses of $\mathcal{O}(200\text{ GeV})$. An order of magnitude on the spin independent direct detection limit would allow to rule out all MSSM neutralinos lighter than 30 GeV while a factor of 2 improvement in sensitivity in gamma-ray searches would probe all neutralinos lighter than 20 GeV, in case that no positive signals are found in these searches. We therefore expect the lower limit on the lightest neutralino mass to keep increasing as the LHC and direct and indirect dark matter searches improve their sensitivity.

ACKNOWLEDGMENTS

We thank Sasha Pukhov for providing the HIGGSBOUNDS interface with MICROMEGAS and Karina Williams for helpful discussions on HIGGSBOUNDS. This work was supported in part by the CNRS-PICS grant "Propagation of Low Energy Positrons."

[1] R. Bernabei *et al.*, Eur. Phys. J. C **67**, 39 (2010).
[2] C. E. Aalseth *et al.* (CoGeNT), Phys. Rev. Lett. **106**, 131301 (2011).
[3] H. K. Dreiner, S. Heinemeyer, O. Kittel, U. Langenfeld, A. M. Weber *et al.*, Eur. Phys. J. C **62**, 547 (2009).
[4] N. Fornengo, S. Scopel, and A. Bottino, Phys. Rev. D **83**, 015001 (2011).
[5] S. Scopel, S. Choi, N. Fornengo, and A. Bottino, Phys. Rev. D **83**, 095016 (2011).
[6] L. Calibbi, T. Ota, and Y. Takanishi, J. High Energy Phys. 07 (2011) 013.
[7] A. V. Belikov, J. F. Gunion, D. Hooper, and T. M. Tait, Phys. Lett. B **705**, 82 (2011).
[8] D. T. Cumberbatch, D. E. Lopez-Fogliani, L. Roszkowski, R. R. de Austri, and Y.-L. S. Tsai, arXiv:1107.1604.
[9] J. Cao, K.-i. Hikasa, W. Wang, J. M. Yang, and L.-X. Yu, J. High Energy Phys. 07 (2010) 044.
[10] D. Feldman, Z. Liu, and P. Nath, Phys. Rev. D **81**, 117701 (2010).
[11] D. A. Vasquez, G. Belanger, C. Boehm, A. Pukhov, and J. Silk, Phys. Rev. D **82**, 115027 (2010).
[12] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
[13] A. Bottino, N. Fornengo, and S. Scopel, Phys. Rev. D **67**, 063519 (2003).
[14] D. Hooper and T. Plehn, Phys. Lett. B **562**, 18 (2003).
[15] A. Bottino, F. Donato, N. Fornengo, and S. Scopel, Phys. Rev. D **68**, 043506 (2003).
[16] G. Belanger, F. Boudjema, A. Cottrant, A. Pukhov, and S. Rosier-Lees, J. High Energy Phys. 03 (2004) 012.
[17] P. Belli, R. Bernabei, A. Bottino, F. Cappella, R. Cerulli *et al.*, Phys. Rev. D **84**, 055014 (2011).
[18] D. Benjamin *et al.* (Tevatron New Phenomena) and (Higgs Working Group), arXiv:1003.3363.
[19] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **106**, 231801 (2011).
[20] S. Chatrchyan *et al.* (CMS Collaboration), Report No. CMS PAS HIG-11-011, 2011.
[21] D. A. Vasquez, G. Belanger, and C. Boehm, arXiv:1107.1614.
[22] A. Bottino, F. Donato, N. Fornengo, and S. Scopel, Phys. Rev. D **70**, 015005 (2004).
[23] J. Lavalle, Phys. Rev. D **82**, 081302 (2010).
[24] D. Cerdeno, T. Delahaye, and J. Lavalle, Nucl. Phys. **B854**, 738 (2011).

[25] I. Gogoladze, R. Khalid, S. Raza, and Q. Shafi, Mod. Phys. Lett. A **25**, 3371 (2010).

[26] E. Aprile *et al.* (XENON100), Phys. Rev. Lett. **105**, 131302 (2010).

[27] G. Belanger, F. Boudjema, C. Hugonie, A. Pukhov, and A. Semenov, J. Cosmol. Astropart. Phys. 09 (2005) 001.

[28] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun. **180**, 747 (2009).

[29] G. Belanger, F. Boudjema, P. Brun, A. Pukhov, S. Rosier-Lees *et al.*, Comput. Phys. Commun. **182**, 842 (2011).

[30] A. Djouadi, J.-L. Kneur, and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007).

[31] E. Komatsu *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **180**, 330 (2009).

[32] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, Comput. Phys. Commun. **181**, 138 (2010).

[33] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, Comput. Phys. Commun. **182**, 2605 (2011).

[34] A. Abdo, M. Ackermann, M. Ajello, W. Atwood, L. Baldini *et al.*, Astrophys. J. **712**, 147 (2010).

[35] J. Baglio and A. Djouadi, arXiv:1103.6247.

[36] A. Nikitenko, in Implications of LHC results for TeV-scale physics, CERN, 2011 (unpublished).

[37] J. Giedt, A. W. Thomas, and R. D. Young, Phys. Rev. Lett. **103**, 201802 (2009).

[38] Z. Ahmed *et al.* (The CDMS-II), Science **327**, 1619 (2010).

[39] J. F. Navarro, C. S. Frenk, and S. D. White, Astrophys. J. **490**, 493 (1997).

[40] M. Walker, C. Combet, J. Hinton, D. Maurin, and M. Wilkinson, Astrophys. J. **733**, L46 (2011).

[41] A. Charbonnier, C. Combet, M. Daniel, S. Funk, J. Hinton *et al.*, arXiv:1104.0412 [Mon. Not. R. Astron. Soc. (to be published)].

[42] J. Collar, arXiv:1106.0653.

[43] G. Wilkinson, Report No. HEP-EPS 2011, Grenoble, 2011 (unpublished).

[44] M. Paluton, in Beauty 2011, Amsterdam, 2011.

[45] I. Vivarelli, Report No. HEP-EPS 2011, Grenoble, 2011.

[46] J. A. Conley, H. K. Dreiner, and P. Wienemann, Phys. Rev. D **83**, 055018 (2011).

[47] V. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **680**, 34 (2009).

[48] R. Forrest (CDF Collaboration), arXiv:0910.1931.